Zooming through the MIST

Mathew Owens, Oliver Allanson and Megan Maunder report on the 51st annual Magnetosphere, Ionosphere, and Solar–Terrestrial (MIST) meeting.

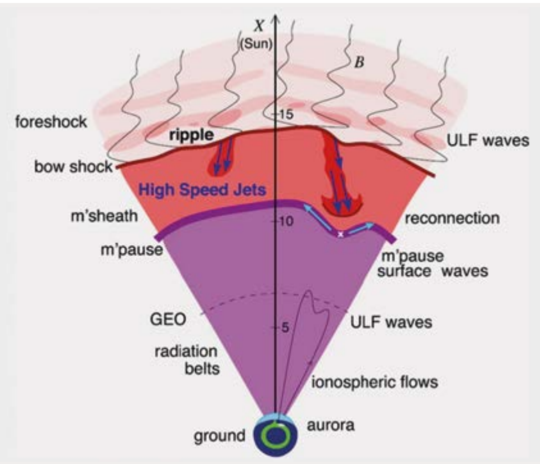
Autumn MIST went ahead on 19 and 20 November 2020, albeit with some changes. The Geological Society at Burlington House was out-of-bounds because of lockdown restrictions, moving MIST online for the first time. With no need to consider travel arrangements, but being open to the possibility of participants attending around existing engagements, we instigated a format change, with talks and posters spread over two short days instead of the usual one.

By all accounts it was a success, with surprisingly few technical hitches and a record attendance of more than 100 simultaneous participants. Video conferencing, so familiar to all in 2020, provided a reasonable approximation of in-person talks and saw a good level of engagement in the subsequent question-and-answer sessions.

The difficulty with online conferences is providing a substitute for poster sessions and the informal discussions that occur over lunch, coffee or a post-conference pint. We trialled the gather.town platform for poster sessions, which allows attendees to move between posters and discussions. Feedback was again positive, respondents commenting that it was as close an approximation of in-person poster sessions as is possible at the moment and afforded a good level of interaction – but the lack of wine was noted.

Solar–terrestrial connections

There was an impressive breadth of work on display at the 2020 meeting, spanning the full remit of MIST science, from the solar surface to the magnetospheres of Earth and the outer planets, with the solar–terrestrial connection remaining a strong theme. Sandra Chapman's (University of Warwick) invited talk encapsulated this, by considering the Sun–Earth system holistically. Historical ground-based observations were used to infer the behaviour of the most energetic forms of solar activity. As such extreme space weather is by its very nature rare, long records are required for its analysis. Using the approximately 150-year *aa* record of geomagnetic activity, the occurrence of hazardous space weather was shown to follow the approximately 11-year solar clock, most visible in terms of sunspot number. Additionally, Chapman looked at the occurrence of space weather with the Hale cycle, composed of two consecutive sunspot cycles and thus taking approximately 22 years. In odd-numbered sunspot cycles, geomagnetic activity peaks about a year earlier than in even-numbered cycles. This is particularly clear in less severe geomagnetic activity, which recurs every 27 days as the Sun rotates and exposes Earth to similar solar wind conditions.



1 *Solar wind interactions with ripples on the terrestrial bow shock can generate high-speed jets that impact the magnetopause.* (From Plaschke *et al.* 2018)

There is currently a great deal of interest in the physical processes by which the solar wind couples to the terrestrial system and provides the energy input that ultimately drives geomagnetic activity. These processes can be highly localized in space and time, but nevertheless they are influenced and driven by the global system. Thus, multi-spacecraft missions have been pivotal to our understanding. The four Cluster spacecraft remain extremely valuable for disentangling the spatial and temporal variations within the large-scale magnetospheric system. More recently, the four-spacecraft Magnetospheric Multiscale (MMS) and the five-spacecraft Time History of Events and Macroscale Interactions during Substorms (THEMIS) missions have enabled analysis on much smaller scales, with spacecraft separations down to a few kilometres.

Sadie Robertson (Imperial College London) reported on a study of small flux ropes, helical magnetic structures that form as the magnetic field carried by the solar wind reconnects with the Earth's own magnetic field. The reconnection occurs at the magnetopause and results in field lines connected to both the Earth and the solar wind. Robertson argued that the topology of the flux ropes can reveal how magnetic flux is stripped away from the dayside magnetosphere and transported to the nightside tail, as well as being an important site for particle acceleration. The clustering of flux ropes suggests that the production rate is not constant in time or uniform in space, indicating that dayside reconnection is bursty in nature.

The bursty nature of the solar wind–magnetosphere interaction was also highlighted by Adrian LaMoury (Imperial College London). As the solar wind flow is faster than any plasma or magnetic wave speed that it can support, a standing shock wave – the bow shock – forms when the solar wind encounters the stationary magnetosphere. High-speed jets have been observed in the magnetosheath, the compressed solar wind bounded by the bow shock and the magnetopause. They are thought to be caused by the solar wind flowing through ripples on the bow shock, and may have space-weather consequences by triggering waves or reconnection on the dayside magnetopause (figure 1). LaMoury examined the conditions under which jets are likely to survive all the way from the bow shock to the magnetopause and showed that this happens when the solar wind speed and/or magnetic field intensity are enhanced.

When the solar wind magnetic field is orientated northwards, reconnection tends to move from the dayside magnetopause, up to beyond the cusps, the outward projections of the Earth's magnetic poles. Unlike dayside reconnection, this is not necessarily expected to add flux to the nightside and produce reconnection in the tail. Laura Fryer (Southampton University) used Cluster data to examine the evolution of the magnetospheric flux under northward heliospheric magnetic field. For the three events considered, the observations were all consistent with tail reconnection.

One difficulty with such analyses is objectively determining the different spatial regions within the magnetosphere that the spacecraft pass through, such as the cusps, the tail lobe, the plasma sheet etc. The boundaries between different regions are in continual motion and there are intrinsic time variations in the magnetic and plasma properties. While an expert observer can classify data into different magnetospheric regions, this is not practical for large volumes of data from multi-spacecraft missions. **Mayur Bakrania** (University College London) looked at machine-learning solutions to this problem. The algorithm was able to distinguish successfully between different regions but, perhaps even more interestingly, the unsupervised approach (see box "Machine learning") identified a number of populations that have historically been considered a single region.

Planetary physics

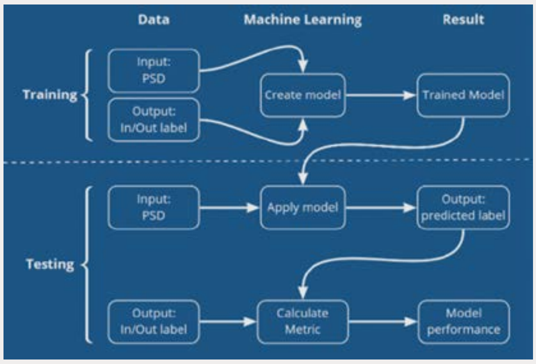
MIST has a prominent planetary physics strand, with comparative studies both informing and deriving from an understanding of the more accessible terrestrial system. Saturn and Jupiter are of particular interest because of their large magnetospheric systems and the availability of detailed *in situ* observations from the Cassini and Juno missions, as well as remote observing possibilities. Unlike the terrestrial system, both Saturn and Jupiter have large internal sources of plasma that distort the magnetospheric systems. The internal plasma sources, coupled with fast rotation, stretch out the dipolar fields into a magnetodisc. This leads to a "cushion region" where the stretched field lines reconnect and convect around with the magnetodisc until they reach the magnetopause. This has been observed at Jupiter, but not at Saturn. **Ned Staniland** (Imperial College London) analysed Cassini data to show the existence of a cushion region at Saturn, though only a few rare examples could be found. Unlike at Jupiter, it forms at dusk rather than dawn, probably arising from asymmetric heating of the plasma in the disc.

At Jupiter, the X-ray aurora yield insight into the larger magnetospheric system. **Dale Weigt** (University of Southampton) used 28 observations collected over a 20-year period from the Chandra mission to study Jupiter's X-ray hotspot and better understand its magnetospheric driver. The northern-hemisphere hotspot is brighter than its southern-hemisphere counterpart. The aurora appears to arise from ion populations at noon and on the dusk flank, which may be related to ultra-low-frequency wave activity along the magnetopause.

Radio observations of Saturn allow the temporal and spatial variations in broadband hiss to be inferred. **Emma Woodfield** (British Antarctic Survey) coupled these observations with models of Saturn's magnetic field and plasma, in order to model Saturn's radiation belts in much the same way as is done for Earth. At Earth, hiss generally increases electron diffusion and results in a loss of electrons to the atmosphere. Woodfield showed that at Saturn, hiss generally increases the electron density in the radiation belt as local acceleration dominates over diffusion-driven losses. The reason for this difference is largely the location of the hiss, which is confined to higher latitudes at Saturn where plasma density is low.

Much of our understanding of the global magnetospheres of the outer planets comes from the interpretation of observations through models. **Josh Wiggs** (Lancaster University) argued that the loading of Jupiter's magnetosphere with plasma from the volcanic moon Io, and the subsequent small-scale structures in radial plasma transport, is best tackled with a combination of kinetic and magnetohydrodynamic physics. For this reason, Wiggs is developing an open-source hybrid code, in which the ions are treated with kinetic physics, while the electrons are treated as a conducting fluid. The code was demonstrated to capture the necessary diffusion, gyromotion and plasma

1 Machine learning



2 *General framework for training and testing a supervised machine-learning algorithm to predict whether a point is inside or outside the radiation belt (the output) on the basis of the observed power spectral density (the input).* (Téo Bloch)

As in many scientific disciplines, the use of machine learning is being increasingly adopted by the MIST community. At Autumn MIST it featured in talks and posters from across the spectrum, from the solar wind to the radiation belts. The two broad categories of machine learning are supervised, where an algorithm is initially trained using an existing set of examples (typically assembled by an expert observer; figure 2), and unsupervised, where the data itself determines the output purely based on the data itself. Within the MIST community, we're seeing increasing use of supervised machine learning to help apply labour-intensive classification schemes to large datasets. Meanwhile, unsupervised machine learning is revealing order in the data that was not previously apparent.

wave dynamics needed to model the dominant processes operating in the magnetospheres of the outer planets.

Closer to home, Mars and Venus have very different interactions with the solar wind compared to Earth and the outer planets. In the absence of a strong planetary magnetic field, the ionopause serves as the boundary between the planetary system and the solar wind. At Venus, the ionopause separates hot and cold plasmas and hence is well characterized by a discontinuity in electron temperature. At Mars, the ionopause has rarely been identified, possibly because the weak crustal fields mean that it is typically magnetized. **Beatriz Sánchez-Cano** (University of Leicester) developed a new algorithm based on data from the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft to improve the identification of the ionopause. Surprisingly, the occurrence and height of the ionopause was broadly similar over the northern and southern hemispheres, despite the enhanced crustal magnetic fields in the south (figure 3).

The heliosphere

Heliospheric physics is also undergoing something of a renaissance, with exciting new near-Sun observations being returned from both Parker Solar Probe (PSP) and Solar Orbiter. These missions are allowing a new understanding of how the solar wind is released and accelerated before arriving at Earth.

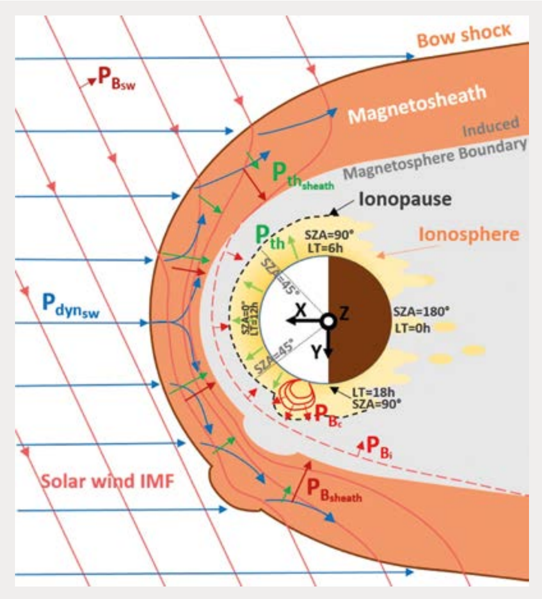
Heat carried by the mobile electrons in the corona is central to some models of solar wind formation. **Joel Baby Abraham** (Mullard Space Science Laboratory) examined the electron distributions observed *in situ* by PSP to look for fingerprints of solar wind acceleration. The PSP observations have a high cadence, so there is a lot of data to process; thus, machine-learning methods were used alongside more traditional "fitting" of the distribution functions. The thermal electron density is found to decrease with distance from the Sun as expected from a simple spherical expansion, even very close to the Sun. However, the more energetic components of the electron distribution exhibit much more complex behaviour, which may suggest a high-energy beam of electrons aligned with the magnetic field close to the Sun that becomes increasingly scattered with distance.

Both the energization and the scattering of electrons is likely to result from wave–particle interactions. When

"At Jupiter, the X-ray aurora yield insight into the larger magnetospheric system"

2 Autumn MIST in posters

● **Jeffersson Andres Agudelo Rueda** (Mullard Space Science Laboratory). Study of plasma bulk profiles along artificial-spacecraft trajectories through a 3D fully kinetic simulation of turbulent magnetic reconnection
● **Oliver Allanson** (Northumbria University). Diffusion and advection during nonlinear electron–whistler interactions
● **Martin Archer** (Imperial College London). How do I demonstrate impact from my drop-in public engagement activity? A novel approach from a space soundscape exhibit
● **Luke Barnard** (University of Reading). Ensemble CME modeling constrained by Heliospheric Imager observations
● **Sarah Bentley** (Northumbria University). Random forest models of magnetospheric ULF wave power
● **Laura Bercic** (Mullard Space Science Laboratory). The interplay between ambipolar electric field and Coulomb collisions in the solar wind acceleration region
● **Aisling Bergin** (University of Warwick). Quantifying the statistical variation of return period, amplitude and duration of bursts in the AE index across successive solar cycles
● **Daniel Billett** (University of Saskatchewan, Canada). Ion-neutral coupling in the E- and F-regions during a substorm
● **Gemma Bower** (University of Leicester). Transpolar arcs: seasonal dependence identified by an automated detection method
● **Nathan Case** (Lancaster University). Inner magnetospheric response to the IMF by 2 component: Van Allen Probes and Arase observations
● **Shahbaz Chaudhry** (University of Warwick). Network analysis of Pc waves using the SuperMAG database of ground-based magnetometer stations
● **Dave Constable** (Lancaster University). Predicting field-aligned currents in the jovian mid-magnetosphere
● **John Coxon** (University of Southampton) Hot plasma in the magnetotail lobes shows characteristics consistent with closed field lines trapped in the lobes
● **Diego de Pablos** (Mullard Space Science Laboratory). Analysis of time-domain correlations between EUV and *in situ* observations of coronal jets
● **Elizabeth Donegan-Lawley** (Birmingham University). High latitude statistical modelling for scintillation of GNSS signals
● **Xiangcheng Dong** (RAL Space). *In situ* observation of secondary magnetic reconnection region beside ion-scale flux rope at the magnetopause
● **Tom Elsden** (University of Leicester). Evolution of high-m poloidal Alfvén waves in a dipole magnetic field
● **Tadhg Garton** (University of Southampton). Machine learning applications to magnetospheric reconnection identification
● **Imogen Gingell** (University of Southampton). Inverted rope-like structures in the bow shock's transition region
● **Adrian Grocott** (Lancaster University). TiVIE: the



3 *The solar wind interaction with the martian system can lead to the formation of the ionopause, where a balance is achieved between ionospheric thermal pressure, magnetic pressures and the upstream solar wind dynamic pressure.* (From Sánchez-Cano *et al.* 2020)

plasma instabilities occur, waves extract energy from the particles. When wave damping occurs, the particles extract energy from the waves. Seong-Yeop Jeong (Mullard Space Science Laboratory) used quasi-linear diffusion theory to model the scattering of the energetic electron beam. Jeong concluded that instabilities due to whistler waves – low-frequency electromagnetic waves – can change the properties of the beam, but to explain the observed trends fully, other mechanisms such as Coulomb collisions of particles are also required. The spiral geometry of the heliospheric magnetic field may also be important.

Thomas Woolley (Imperial College London) focused on magnetic switchbacks, rapid reversals in the heliospheric magnetic field direction that may be related to solar wind formation. Switchbacks are Alfvénic, meaning the magnetic field deflections are accompanied by a change in the solar wind velocity. Despite both positive and negative magnetic field deflections, switchbacks always exhibit higher speeds than the surrounding plasma. Because faster solar wind is generally hotter than slower solar wind, one might expect switchbacks to be hotter than the surrounding solar wind, but Woolley reported that this is not the case. He suggested that they may be formed by a local perturbation of the magnetic field, rather than being bursts of solar wind of different origin.

Looking at much larger scales, Megan Maunder (University of Exeter) turned to an older but equally rich dataset from the Ulysses spacecraft, which explored the polar solar wind. Pure, fast solar wind is confined to the polar regions at solar minimum. Because the fast wind has low density, large solar eruptions of plasma and magnetic field – coronal mass ejections (CMEs) – embedded in it undergo pressure-driven over-expansion, and produce shock waves both ahead and behind. Maunder examined an interplanetary CME encountered by a number of heliospheric spacecraft that straddled a region of fast and slow wind. It differed from classic over-expanding CMEs, with shocks attributed to dynamic interaction with the surrounding solar wind rather than exclusively from expansion.

National collaborative projects

Missions are not the only force shaping MIST science. Many large, multi-institution projects have resulted in a recent burst of coordinated research within certain areas of the MIST community. Several applications-focused collaborative projects resulting from the Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) funding line are just spinning up and are likely to feature in future MIST meetings. At the 2020 Autumn MIST, there was a particularly strong showing from radiation belt researchers, many of them involved with the Rad-Sat NERC highlight topic; the detailed new observations from the twin Van Allen Probe spacecraft have undoubtedly contributed too.

The radiation belts are a major space weather concern because of their variable population of relativistic electrons, which are a direct threat to spacecraft hardware. The local energetic electron population is highly sensitive to fluctuating electric and magnetic fields, which are both the source of new energetic electrons through local acceleration and the drivers of diffusion, causing a net movement of electrons. The relation between waves and electron diffusion is complex and difficult to simulate numerically directly from first principles. Instead, real-time forecasting of the radiation belts is achieved by assuming that the evolution of the electron distribution function can be approximated by a diffusion coefficient, which is parameterized on the basis of the wave power. Jasmine Kaur Sandhu (Northumbria University) presented a study of the effect of ultra-low-frequency (ULF) waves and showed that the parameterizations currently used in radiation belt forecast models are severely underestimating diffusion during geomagnetic storms. Sandhu provided storm-time-specific diffusion coefficients for use in future simulations.

With increasing wave power, the total radiation belt electron population can both increase, by local acceleration, or decrease, as a result of enhanced diffusion that can scatter electrons onto trajectories that intersect with the atmosphere so that they are lost. Samuel Walton (University College London) looked at the outer radiation belt population using 12 years of Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) data. Walton showed that geomagnetic storms lead to complex spatial

Time-Variable Ionospheric Electric Field Model
● **Richard Haythornthwaite** (Mullard Space Science Laboratory). Coupled cation-neutral-anion winds in Titan's thermosphere/ionosphere
● **Greg Hunt** (Imperial College London). The response of Saturn's dawn field-aligned currents to magnetospheric conditions during the proximal orbits
● **Matt James** (University of Leicester). The Lomb–Scargle based inner magnetospheric plasma model
● **Joe Kinrade** (Lancaster University). The statistical morphology of Saturn's equatorial energetic neutral atom emission
● **Ronan Laker** (Imperial College London). Statistical analysis of orientation, shape and size of solar wind switchbacks
● **James Lane** (Lancaster University). Dynamics of variable dusk–dawn flow associated with magnetotail current sheet flapping
● **Mike Lockwood** (University of Reading). Universal time variations in the magnetosphere and space weather
● **Allan Macneil** (University of Reading). Increasing occurrence of inverted heliospheric magnetic fields from 0.3 to 1 au
● **Michaela Mooney** (Mullard Space Science Laboratory). Evaluating auroral forecasts against satellite observations
● **David Nunn** (University of Southampton). The 1D numerical modelling of lower band VLF chorus generation using a VHS Vlasov code
● **David Price** (University of Southampton). High-resolution optical observations of neutral heating associated with the electrodynamics of an auroral arc
● **John Ross** (British Antarctic Survey). A new approach to constructing models of electron diffusion by EMIC waves in the radiation belts
● **Robert Shore** (British Antarctic Survey). Real-time forecasts of storm-time geomagnetic activity at UK latitudes from an empirical model
● **Andy Smith** (Mullard Space Science Laboratory). Probabilistic forecasts of storm sudden commencements from interplanetary shocks using machine learning
● **David Stansby** (Mullard Space Science Laboratory). Sensitivity of solar wind mass flux to coronal temperature
● **Emma Thomas** (University of Leicester). Unearthing Uranus's infrared aurora
● **Daniel Verscharen** (Mullard Space Science Laboratory). Scaling the latitudinal dependence of solar wind moments from Ulysses to the inner heliosphere
● **James Waters** (University of Southampton). Multipoint remote observations of auroral kilometric radiation (AKR)
● **Dong Wei** (Southern University of Science and Technology, China). Intense dB/dt variations driven by near-Earth bursty bulk flows (BBFs): a case study
● **Affelia Wibisono** (Mullard Space Science Laboratory). Jupiter's X-ray aurora during a mass injection and Io mass loading event observed by Hubble and Hisaki
● **Lloyd Woodham** (Imperial College London). Enhanced proton parallel temperature inside patches of switchbacks in the inner heliosphere

and temporal patterns of electron increases and loss, with trends in the outermost region of the radiation belt often opposing those closer to Earth.

Part of the difficulty encountered in simulating the radiation belts is that the outer boundary of the radiation belts, and hence the size of the simulation domain, is difficult to define. **Téo Bloch** (University of Reading) used supervised machine learning to determine the average location of the outer boundary using electron distributions observed by the THEMIS spacecraft. The approach was iterative, to define a range of possible outer boundary locations and see which produced the largest separation between the two sets of electron distributions. The best location was found to be further out than is typically used in radiation belt models, suggesting that modellers need to expand the spatial domain that their models cover.

There was also discussion of the proton radiation belt, which sits closer to Earth than its electron counterpart. A significant source of radiation belt protons is "direct capture" of either solar energetic particles or galactic cosmic rays. These protons are captured close to the Earth and diffuse outwards. **Alexander Lozinski** (British Antarctic Survey) demonstrated that, much as for electrons in the outer belt, diffusion coefficients used in current models are too low to explain the available observations.

A second NERC highlight topic, the Solar Wind Impacts on Ground Systems (SWIGS), addresses the effect of geomagnetically induced currents (GICs) on the power system. This brings together a wide range of MIST science. **Lauren Orr** (Lancaster University) looked at the geomagnetic variations in the European magnetometer array during large storms and the subsequent GIC effect on a model of the UK network (figure 4). Using wavelets to identify storm-associated changes in magnetometer data and GIC model results, Orr identified correlations between the ~400 grounded nodes of the UK power transmission network. It is hoped that a few key nodes can be identified for GIC monitoring, which will provide useful information about most of the UK network. It was found that there is high correlation between nodes in the east and the west, but rarely a comparable pattern across latitude bands.

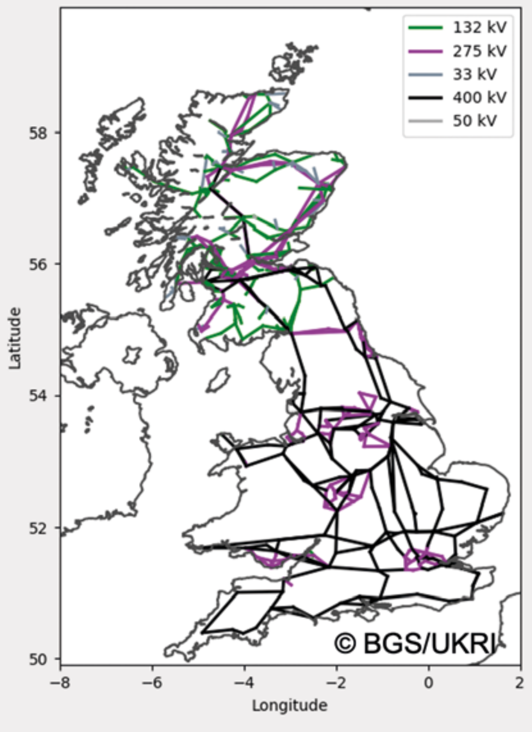
Constraints, challenges and opportunities

The meeting continued the recent trend of very large numbers of attendees and submitted abstracts, including 40 posters that demonstrate the breadth and depth of topics covered (see box "Autumn MIST in posters"). This suggests that we have a healthy and increasingly connected MIST community, which bodes very well for the future.

The traditional one-day schedule (or two half-days as was the case for 2020) now bursts at the seams, with oral abstract submissions significantly outweighing possible provision within those constraints. Furthermore, with recent years' attendance now pushing towards (and just above) the 100-person mark, we have also been pushing the limits of physical capacity at the RAS and the Geological Society for posters and refreshments. Holding the meeting online in 2020 removed any concerns regarding space, and clearly brings a number of accessibility and environmental benefits.

However, MIST Council and the community at large recognize the many intangible benefits of holding in-person meetings for the effectiveness of scientific communication and collaboration, but also for community vibrancy and collegiality. MIST Council will seek further feedback and guidance from the community on possible future tactics for Autumn MIST meetings, bearing in mind the various – and very welcome – challenges and opportunities that increasing levels of participation present. As always, please contact mist.council@gmail.com with any suggestions, feedback or questions.

MIST Council would like to thank all attendees and presenters for contributing to an engaging and fruitful meeting. In particular, we would like to thank the RAS for the use of their Zoom licence, and Richard O'Sullivan for his help with the hosting of the meeting. If you would like to propose a theme for Autumn MIST 2021, please contact MIST Council. ●



4 *The UK's high-voltage power transmission network is susceptible to extreme space weather through geomagnetically induced currents.* (Lauren Orr)

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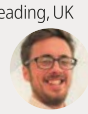

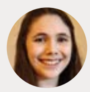

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